UNITED
NATIONS

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General Assembly

Distr.
LIMITED

A/AC.105/C.1/L.187
16 February 1993

ORIGINAL: ENGLISH

COMMITTEE ON THE PEACEFUL USES OF
OUTER SPACE
Scientific and Technical Subcommittee
Thirtieth session
Agenda item 7

USE OF NUCLEAR POWER SOURCES IN OUTER SPACE

Safety principles for nuclear power sources in space revisited

Working paper submitted by the United Kingdom of Great Britain and Northern Ireland

The following paper attempts to summarize the achievements to date in formulating the principles relating to the use of nuclear power sources (NPS) in outer space. The working paper also suggests a number of ways in which the principles could be further improved.

Introduction

The event which led to the formulation of principles relevant to the use of nuclear power sources (NPS) in outer space by the Committee on the Peaceful Uses of Outer Space was the arrival in northern Canada of debris from Cosmos 954 on 24 January 1978. This event highlighted the risk to all countries from NPS in space, not just to the few countries actively involved in launching these devices. That it took over a decade to reach agreement on a set of principles reflects the technical nature of the subject covered by the principles as well as the initial diversity of views among the many countries concerned about the hazards from NPS in space. That agreement was reached in 1992 and reflects the determination of those countries to reach an international consensus.

Yet the adoption of the principles was accompanied by the recognition that the process of revision should begin immediately. The form of some of the principles reflected the state of space NPS technology in the 1980s, already being overtaken by new developments. Ideally, principles should be

technology-independent so that the requirement for change is infrequent. For example, a kilogram of plutonium-238 is more toxic than a kilogram of plutonium-239 by a factor of around 250 (virtually identical to the ratio of their half-lives) but the principles allow plutonium-238 fuelled thermionic generators (RTGs) but not plutonium-239 fuelled reactors: the assumption that reactor containment standards will always be worse than those of RTGs by a factor of 250 is only of short-term validity. The principles do not deal adequately with nuclear propulsion which is now under serious development and there is no adequate definition of a "safe orbit" because, to date, the problem of space debris has not been properly addressed.

The tremendous effort put into the development of the principles adopted in 1992 was an essential foundation to the establishment of an international safety regime for the use of NPS in space. It is now proposed to build on that structure taking account of recent technical advances and parallel developments in related safety fields.

Terrestrial experience

Experience with land-based reactors seems to provide some useful pointers to the best way to proceed. Terrestrial radiological safety principles have become highly developed under the aegis of the International Commission for Radiological Protection (ICRP). This has been recognized in the existing "principles" though with some departure from the ICRP philosophy. The latest ICRP-60 recommendations are particularly helpful through the extension of the earlier versions to accidents not involving acute deaths.

Terrestrial reactor safety principles have developed independently in many countries. Advances in probabilistic risk assessment (see, for example, the proceedings of the International Atomic Energy Agency (IAEA) conference at Vienna from 3 to 7 June 1991, and International Nuclear Safety Group INSAG-6, 1992) have led to substantial convergence of national views, and the IAEA General Conference in September 1991 recommended that the Director General prepare an outline of a nuclear safety convention. The groundwork for this had already been laid by the Agency's standing groups, particularly the International Nuclear Safety Advisory Group (see INSAG-3, 1988). An IAEA publication on safety fundamentals is imminent, defining safety objectives and their impact not only on technical aspects of design, construction, operation and decommissioning, but also on management and the influence of human factors.

The difference between safety considerations for land-based and space NPS arises mainly from the large difference in perceived transnational risk. Land-based systems hazard mainly the country of origin, with sites near to national borders sometimes dealt with under bilateral agreements. Systems destined for operation in outer space give rise to some risk in the country of origin (probably the majority of the total risk) but the perceived risk is to all the countries which could be subject to impact on re-entry to the atmosphere, particularly under accident (i.e., uncontrolled) conditions. However, this difference is a matter of degree rather than of principle. The safety principles developed for land-based systems should be applicable in

space systems, a point noted in the preamble to INSAG-3. The principles for protecting people should be independent of their nationality.

A starting-point

There are a number of themes involved in establishing a safety regime which emerge clearly from the ICRP and IAEA publications:

(i) Nuclear activities should only be undertaken if there is a net positive benefit, i.e., the benefits outweigh the detriments. Examples of activities which probably fail this test are the wearing of radioactive jewellery; exploring caves with high natural radon levels; atmospheric weapon tests; and satellite missions in Earth orbit which can obtain sufficient power from solar arrays of manageable size;

(ii) The maximum risk arising should be limited to an acceptable level. In practice, different risk levels are commonly used for workers and the general public, in recognition that the worker gains more benefit than the rest of society; and for accidents involving a risk to a group of people rather than single isolated individuals, in recognition that society finds the death of a coherent group (family, football team, plant operators, tourist party, village) to be more traumatic and less acceptable than the same number of deaths scattered among unrelated groups. As well as limiting individuals and societal risks, consideration of damage to the natural and built environment is also required;

(iii) Nuclear risks should be as low as reasonably achievable taking into account social and economic factors. This is the ALARA principle of ICRP which has its counterpart in reactor safety. Some risks are easy to guard against and can be effectively eliminated at reasonable cost, while others are technically difficult or economically expensive to reduce much below the maximum risk limit. The cost of reducing risks should be optimized against the benefit gained. ICRP has introduced the concept of dose constraints at levels below the dose limits to assist in the process of optimization, with the constraints set according to the local situation;

(iv) Those carrying out nuclear activities should adopt a safety culture, that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear safety issues receive the attention warranted by their significance (INSAG-4, 1991). The safety culture has two general components: the safety-related framework within an organization and the commitment of management to its role, and the attitude of individuals at all levels in responding to this framework.

Although ICRP has not adopted a fully risk-based approach to radiological protection and IAEA is at a formative stage in developing an internationally accepted reactor safety regime, it is proposed that the way forward for the Committee on the Peaceful Uses of Outer Space in revising the "principles" should be a combined risk limitation/safety culture philosophy applied only to the transnational risk (recognizing that considerations of sovereignty preclude the Committee from monitoring national regulations) making maximum use of the ICRP and IAEA groundwork.

Tolerable and acceptable risks

A number of studies have analysed the acceptability of risk and identified factors involved, generally using fatal risks as a measure of hazard. Higher levels of risk are acceptable for those entered into voluntarily than for those imposed by others. Higher levels of risk are acceptable by those who benefit directly from the activity causing the risk. It can thus be expected that the acceptable level of transnational risk from NPS in outer space, an involuntary risk from an activity of only indirect benefit, will be at the lower end of the spectrum of acceptable risks.

Workers in an industry have some understanding of the risks they run and some choices in the matter. The maximum level of fatal risk in high risk groups within relatively risky industries in the United Kingdom is about 1 in 1,000 per year. This level of risk is only exceeded by deep-sea fishermen (1 in 750) and by workers in oil and gas extraction (1 in 990). The average radiation worker receives around 1 mSv per year, corresponding to an annual risk of 1 in 20,000, half the level of risk for the construction industry, while the average fatal risk for all manufacturing industry is 1 in 50,000, the safest occupations having risks of less than 1 in 100,000.

For the general public the risk of death by road accident, which may be considered largely voluntary, is 1 in 10,000 in the United Kingdom, and for all accidents 1 in 4,000. The risk corresponding to the ICRP public dose limit of 1 mSv per year is 1 in 20,000. The risk from a gas explosion at home (involuntary) is 1 in a million and from lightning 1 in 10 million.

Two risk levels can be conveniently identified from this type of analysis. First, there is the maximum tolerable fatal individual risk, above which risks are unacceptable. For involuntary risks to the general United Kingdom public this seems to be about 1 in 10,000 per year, about the same as for traffic accidents or a little lower than the risk from other accidents. Secondly, there is the generally acceptable individual risk which is normally ignored. This seems to be about 1 in a million for involuntary public risks; below this level of risk there seems to be no significant degree of concern.

Between these two levels (10^{-4} to 10^{-6} per year) the individual risk is generally acceptable, but reductions which can be achieved at acceptable social and economic cost are expected to be implemented. Higher standards of safety seem to be needed where the risk is to a coherent group of people rather than an individual. Terrestrial reactor safety studies suggest that

the maximum tolerable individual risk should be divided by the number (N) of fatalities, giving a maximum societal risk of 1 N x 10^{-4}. However, if the risk is spread out among a large population (as for world-wide atmospheric dispersion of radionuclides), the individual limit seems to be appropriate.

Protecting the natural and built environment is a more subjective process. In the context of land-based nuclear reactors, the main consideration seems to relate to the choice of site in relation to thermal pollution, visual intrusion and important habitats of natural species, particularly the human species. In space the environmental considerations are different and less well developed. There is a generally accepted view that contamination of Earth orbits should be avoided, although accumulating used space reactors in high Earth orbit has been considered acceptable. Certainly the interference with orbiting and some ground-based scientific experiments from space reactors with a high radiation field has attracted much adverse comment. Atmospheric dispersion on re-entry can give rise to a substantial global collective dose and the cost of this should be justified in comparison with the cost of alternative options, the benefits from the mission and the accumulated global hazard. Dispersion on impact is generally a less onerous event, often capable of mitigation using established decontamination technologies.

It must be emphasized that setting risk limits is a very subjective process. An individual indulging in five hours of solo rock climbing every weekend accepts voluntarily a fatal risk of 1 in 100. Pedestrian deaths in traffic accidents, an involuntary risk with no direct benefit to the risk taker, is around 1 in 30,000, well above the 1 in a million generally acceptable individual risk suggested above. It is necessary to take a rather broad view of tolerability and acceptability to identify corresponding risk value.

Space debris and nuclear safe orbits

One of the advantages of a probabilistic approach to the safety of NPS in outer space is that it extends naturally to considerations of space debris and the definition of safe orbits. Once the tolerable and acceptable risk levels have been defined, it is then purely a question as to whether any particular orbit satisfies these risk criteria, given the hazard from space debris. Similarly, the acceptability of additional debris is a technical question depending on the risk it creates through its impact on satellites. In the longer term, removal of radioactive material from Earth and Earth orbit is likely to be the best solution.

With principle 3 redrafted to use a probabilistic risk assessment, changes in the space debris environment can be readily taken into account.

Safety culture

The major accidents at Three Mile Island and at Chernobyl emphasized that physical safety provisions are not enough. It is also necessary to take account of the people in the system, who in turn respond to the organizational framework in which they are placed. The recognition of this aspect of achieving the required safety standards in terrestrial nuclear safety has led to the concept of safety culture: the commitment of individuals and organizations to the overriding priority of safety.

At an international level there are two established organizations that contribute to the safety culture. The nuclear industry supports the World Association of Nuclear Operators (WANO), dedicated to minimizing the risks of a further accident by improvements at the operational level; WANO operates to a large extent through peer-group pressure that ensures that no member can risk being accused of failing to comply with the spirit of WANO. The second organization, IAEA, commissioned its nuclear safety advisory group to publish a report on the safety culture concept (INSAG-4). Among the many elements it identified as contributing to safety culture are:

- Individual awareness of the importance of safety;

- Knowledge and competence, conferred by training and instruction of personnel and by their self-education;

- Commitment, requiring demonstration at the senior management level of the high priority of safety and adoption by individuals of the common goal of safety;

- Motivation, through leadership, the setting of objectives and systems of rewards and sanctions, and through individuals' self-generated attitudes;

- Supervision, including audit and review practices, with readiness to respond to individuals' questioning attitudes;

- Responsibility, through formal assignment and description of duties and their understanding of individuals.

In the context of NPS in outer space, much of the safety culture provision must be at the level of the country and organizations involved in the particular mission. However, in view of the high perceived risk of transnational accidents, the top layer of safety culture needs to be at the international level. It would be appropriate for the United Nations to act at this level, perhaps through an expert advisory committee to the Secretary-General operating by peer-group pressure to ensure that all satellites with NPS on board are designed, built and operated within an internationally acceptable safety culture.

Conclusions

In an attempt to make the safety principles for NPS in outer space more technology-independent and less likely to need regular revision, a new approach is proposed based on the accumulated experience of achieving acceptable safety standards with terrestrial nuclear power systems. The new principles require NPS systems to demonstrate:

- A net positive benefit;
- A maximum risk to individuals, society and the environment within tolerable limits;
- Risks reduced below these maximum tolerable limits to the extent justified by social and economic costs;
- Design, operation and decommissioning within a safety culture.

Given these principles with minimal elaboration, the remaining tasks for the Committee on the Peaceful Uses of Outer Space are then:

- To agree maximum tolerable and generally acceptable levels of risk;
- To provide the top layer of the safety culture, possibly in the form of an expert group to advise the Secretary-General on the adequacy of the measures taken to implement the new principles.